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Integrated generation-transmission expansion planning for offshore oilfield power systems based on genetic Tabu hybrid algorithm

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Abstract To address the planning issue of offshore oilfield power systems, an integrated generation-transmission expansion planning model is proposed. The outage cost is considered and the genetic Tabu hybrid algorithm (GTHA) is developed to find the optimal solution. With the proposed integrated model, the planning of generators and transmission lines can be worked out simultaneously, which outweighs the disadvantages of separate planning, for instance, unable to consider the influence of power grid during the planning of generation, or insufficient to plan the transmission system without enough information of generation. The integrated planning model takes into account both the outage cost and the shipping cost, which makes the model more practical for offshore oilfield power systems. The planning problem formulated based on the proposed model is a mixed integer nonlinear programming problem of very high computational complexity, which is difficult to solve by regular mathematical methods. A comprehensive optimization method based on GTHA is also developed to search the best solution efficiently. Finally, a case study on the planning of a 50-bus offshore oilfield power system is conducted, and the obtained results fully demonstrate the effectiveness of the presented model and method.

Keywords Offshore oil field power system, Generation expansion planning, Transmission expansion planning, Genetic Tabu hybrid algorithm

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1 Introduction

Offshore oil resource is playing an increasingly significant role in satisfying our fossil fuel needs. According to the U.S. Geological Survey, in 2014, about 47% of the total untapped oil resource comes from the sea [1]. For the offshore oil industry, it is becoming an important issue to reliably supply electrical power to the offshore oil platforms. At present, most of the oil platforms far from the land are powered by the independent power stations built on them. This power supply mode, however, would lead to blackout of the platform once the power station thereon shuts down [2]. Therefore, it becomes a trend to construct offshore oilfield power systems that can interconnect every platform to improve the reliability of power supply [3]. Since 2010, offshore platforms have been connected electrically along the coast of China. Many larger-scale offshore power systems are emerging. Therefore, how to plan a highly reliable power system suitable for the offshore oilfield is critical for the construction as well as the effective and safe operation of the offshore oil industry.

The technology of planning has been widely studied and applied to large-scale inland power systems for the past decades [4–6]. Conventionally, the process of inland power system planning is divided into two steps, i.e., generation expansion planning (GEP) and transmission expansion planning (TEP) [7], for the following reasons: ① It is difficult to deal with GEP and TEP simultaneously due to the huge number of variables [8]. ② The construction of power stations and transmission lines are in the charge of different sections of the power industry [9]. ③ Over 80% of the total expansion cost goes to GEP whereas TEP only accounts for a small fraction of the investment, which leads to relatively minor errors with the two-step planning procedure [10]. Either GEP or TEP has been widely investigated in the past research. For GEP, different techniques have been used [11], for instance, fuzzy logic [12], genetic algorithm (GA) [13], particle swarm optimization (PSO) [14], Tabu search [15] and etc. However, without the geographical information of generators and transmissions, all generators were just considered to be at a single nodal point. As for TEP, there are also different methods discussed in previous literature, for example, mixed integer linear programming (MILP) algorithms [16], heuristic methods [17], game theory [18] and artificial intelligence techniques [19–21]. Similarly, without clear information of generations, the obtained TEP result can hardly be the most cost-effective one [22].

However, the composite generation and transmission system expansion planning is reasonable for offshore oilfield power systems. Three reasons are explained for this idea. First, offshore systems are much smaller than inland systems and have far fewer stations and lines to be planned, which means the number of decision variables is much smaller. Second, both generation and transmission system are constructed and operated by a single company (In China, the company is China National Offshore Oil Corporation). As a result, simultaneous and integrated planning of generation and transmission is feasible in the perspectives of both technology and management. Last but not least, the investment cost of submarine cables is enormous enough to be comparable to that of generators. Consequently, separate execution of TEP and GEP could lead to ill-considered decisions. Overall, integrated planning is not only feasible but also necessary for offshore oilfield power systems [23]. Furthermore, special attention should be paid to two issues for the planning of offshore systems. One is the outage cost, which need be taken into account for the fact that loss of electricity in the offshore oilfield would cause serious damage to drilling equipment or even a complete halt of oil production. The other is the shipping cost, which should be explicitly considered for the reason that the distance from the mainland to offshore platforms is critical for determining the construction costs of generators and cables.

To address the above issues, an innovative planning method for offshore oilfield power systems is proposed in this paper. An integrated generation-transmission expansion planning model is proposed which includes outage cost and shipping cost. A genetic Tabu hybrid algorithm (GTHA) based optimization method has been developed to solve the integrated planning problem to find the optimal plan.

The rest of the paper is organized as follows: Sect. 2 describes the integrated generation-transmission expansion planning model of an offshore oilfield power system. Section 3 elaborates the GTHA-based optimization method for solving the planning problem. In Sect. 4, a 50-bus offshore oilfield power system is used to validate the effectiveness of the proposed model and algorithm. Conclusions are drawn in Sect. 5.

2 Modeling of the integrated planning problem

The main purpose of the integrated planning is to find the most cost-effective expansion scheme of generation and transmission to ensure reliable power supply of the target offshore system [4]. The objective function of the planning model can be expressed as

$$C = \sum\nolimits_{t=1}^{T} \left(GS_t + TS_t + OC_t \right) \tag{1}$$

where C is the total cost; GS_t the investment and operation costs of generation stations; TS_t the investment and operation cost of transmission system; OC_t the outage cost; t the year concerned; and T the planning horizon.

The costs of generation stations, GS_t in (1), can be obtained by

$$GS_t = \sum_{i \in G_{new}} \left(a_{ti} \cdot X_{ti} \right) + \sum_{i \in G} \left(b_{ti} \cdot N_{ti} \right) \tag{2}$$

where i is the number of platform; G_{new} the set of platforms where new generators can be built; G the set of platforms where existing generators are located; a_{ti} the investment costs of new generators on platform i, which includes the construction costs of units and the distance-dependent shipping cost; X_{ti} the decision variable representing the quantity of new generators on platform i; b_{ti} the operation cost of platform i in year t; and N_{ti} the number of generators already in service on platform i.

The cost of transmission system, TS_t in (1), can be calculated by

$$TS_t = \sum_{(i-j) \in N_{AL}} \left(c_{ti-j} \cdot n_{ti-j} \right) + \sum_{(i-j) \in N_L} \left(s_{ti-j} \cdot 8760 \cdot f_t \right) \tag{3}$$

where c_{ti-j} is the investment costs of submarine cables in corridor $i-j$, which also consists of the construction cost and the distance-dependent shipping cost; n_{ti-j} the decision variable representing the number of new transmission cables in corridor $i\!-\!j$; N_{AL} the set of corridors where new cables will be deployed; N_L the set of corridors where existing cables are deployed; s_{ti-j} the transmission loss (kW) along corridor $i\!-\!j$; and f_t the electricity price.

The outage cost, or OC_t in the objective function (1), is further expressed as:

$$OC_t = E_{EENS} \cdot I_Q \tag{4}$$

where E_{EENS} is the expected energy not served, which is given by (5); and I_Q is the loss coefficient.

$$E_{EENS} = \sum\nolimits_{q \in S_F} L_q \cdot P_q \tag{5}$$

where S_F is the set of fault states in which all load buses cannot be supplied completely; q the specific scenario; L_q is the total amount of shed loads; and P_q the occurrence probability of scenario q.

Assuming that the total number of devices (generators and transmission lines) in the power system is $M_q + N_q$, where M_q is the number of devices in operation and N_q the number of devices out of service for the scenario q, P_q can be computed by

$$P_q = \prod_{j \in S_h j=1}^{M_q} \left(1 - P_{qj}\right) \prod_{k \in S_H k=1}^{N_q} P_{qk} \tag{6}$$

where P_{qj} and P_{qk} are the probabilities for devices j and k to be out of service respectively; S_h the set of devices in operation; S_H the set of devices out of service.

The coefficient I_Q in (4) represents the relationship between the amount of curtailed load and the resultant damage. It is expressed by

$$I_Q = \frac{O_a}{E_a} \cdot P_o \tag{7}$$

where O_a, E_a are the average oil production and electricity consumption per year; and P_o is the oil price.

In the integrated planning model, the following constraints have been taken into account:

1) The constraint on construction of new generators: The number of generators to be installed should be a positive integer and less than its maximum value.

$$\sum\nolimits_{t=1}^{T} X_{ti} \le X_{if} \quad X_{ti} \in N^+ \tag{8}$$

where X_{if} is the total number of generators that can be deployed on platform i.

2) The constraint on new cables: Similarly, the number of new submarine cables should be limited by

$$\sum\nolimits_{t=1}^{T} n_{ti-j} \le N_{fi-j} \quad n_{i-j} \in N^+ \tag{9}$$

where N_{fi-j} is the maximum number of cables in corridor $i\!-\!j$.

3) The constraint on power: The total amount of power supplied by all generators should meet the expected load demand with sufficient reserve capacity, or

$$\sum\nolimits_{t=1}^{T_x} \sum_{i \in G} \left(N_{ti} \cdot W_i\right) \ge Dm_t \cdot (1 + R) \tag{10}$$

where T_x is any possible year in the planning horizon; W_i the generation capacity on platform i; Dm_t the load demand in year t; and R the required reserve ratio.

4) The constraints on electricity: The total electricity generated by online machines needs to cover the whole electricity requirement and at the same time has a certain margin, or

$$\sum\nolimits_{t=1}^{T_x} \sum_{i \in G} \left(N_{ti} \cdot W_i\right) \ge Dm_t \cdot (1 + R) \tag{11}$$

where T_{ti} is the annual utilization hours for units on platform i in year t; Em_t the predicted electricity demand; and E the percentage of electricity reserve.

5) Constraints on power flow: As shown in (12), the constraints are represented with two equalities and two inequalities. The first equality indicates that the active power should always be balanced for each platform. The second equality denotes how the output power from platform i is calculated, which actually represents the DC power flow model of the system. Here DC instead of AC power flow is adopted because accurate reactive power is generally not available at the planning stage. What is more, reactive power balance can be easily achieved by var/voltage control of generators and other var compensators, for instance, capacitors and/or reactors, which are generally much cheaper and have less influence on power system planning. The two inequalities specify the ranges of capacity for each generator and cable respectively.

$$\begin{cases} P_{gi} - P_{di} - P_i = 0 \\ P_i = \sum\nolimits_{j \notin i} b_{i-j} \cdot \left(n_{i-j}^0 + n_{i-j}\right) \cdot \theta_{ji} \\ P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \qquad \forall g \in G \\ \left|P_{i-j}\right| \le P_{i-j}^{\max} \quad \forall i-j \in N_L \end{cases} \tag{12}$$

where P_{gi} is the power generated on platform i; P_{di} the power demand on platform i; P_i the active power output from platform i to the rest of the system; b_{i-j} the susceptance of corridor $i\!-\!j$; θ_{ji} the voltage angle between platform j and platform i; $P_{gi}^{\min}$, $P_{gi}^{\max}$ the lower and upper boundaries of active power that can be generated on platform i respectively; P_{i-j} the active power flow from platform i to j; and $P_{i-j}^{\max}$ its upper limit.

By summarizing the above objective function and constraints, the integrated generation-transmission expansion planning model for an offshore oilfield power system can be formulated into the following constrained optimization problem.

$$\begin{array}{l} \min\ C \text{ defined in } (1) \\ \text{s.t. } (8){-}(12) \end{array} \tag{13}$$

However, problem (12) is a constrained optimization problem, which is generally difficult to solve due to the inequality and equality constraints (8–12). Thus the exact penalty function method [24] is used to transform (12) into an unconstrained optimization problem. First, inequalities and equalities (8–12) are rearranged into the forms of $a_i(\boldsymbol{x}) \geq 0 \quad (i = 1, \cdots, M)$ and $b_j(\boldsymbol{x}) = 0 \quad (j = 1, \cdots, N)$, respectively. Then the objective function of the planning model can be expressed as

$$F(\boldsymbol{x}) = C(\boldsymbol{x}) + \sigma \cdot P(\boldsymbol{x}) \tag{14}$$

where $\boldsymbol{x}$ is the decision variable vector, which is constituted of X_{ti} in (2) and n_{ti-j} in (3); $C(\boldsymbol{x})$ the cost defined by (1); σ the big positive constant that functions as the penalty for violating the constraint; and $P(\boldsymbol{x})$ a newly defined function indicating the extent of violation of constraints, which is expressed by

$$P(\boldsymbol{x}) = \sum\nolimits_{i=1}^{M} \phi(a_i(\boldsymbol{x})) + \sum\nolimits_{j=1}^{N} \psi\left(b_j(\boldsymbol{x})\right) \tag{15}$$

where ϕ and ψ are obtained by

$$\begin{cases} \phi = \max[0, -a_i(\boldsymbol{x})] \\ \psi = \left|b_j(\boldsymbol{x})\right| \end{cases} \tag{16}$$

If any constraint is not satisfied, the value of $\sigma \cdot P(\boldsymbol{x})$, as a penalty for the violation, would become extremely large.

Consequently, the original constrained optimization problem (12) is transformed into an unconstrained one, as shown in (17).

$$\min \quad F(\boldsymbol{x}) = C(\boldsymbol{x}) + \sigma P(\boldsymbol{x}) \tag{17}$$

where σ is set as 10^6 in the following case study.

It can be seen that the proposed integrated planning model (17) incorporates the planning of generation and transmission inherently. What is more, both shipping and outage costs are taken into account to reflect the practical investment and the reliability concern.

3 Solution to the integrated planning problem

The integrated planning model (17) is a nonlinear problem of high-dimension solution space. There are two critical issues in solving this problem, i.e., to narrow the searching space and to develop an efficient algorithm that can find a global solution within an acceptable period of time. Here we propose an intelligent optimization method based on GTHA, of which the basic procedure is illustrated as in Fig. 1. It is carried out through the following steps.

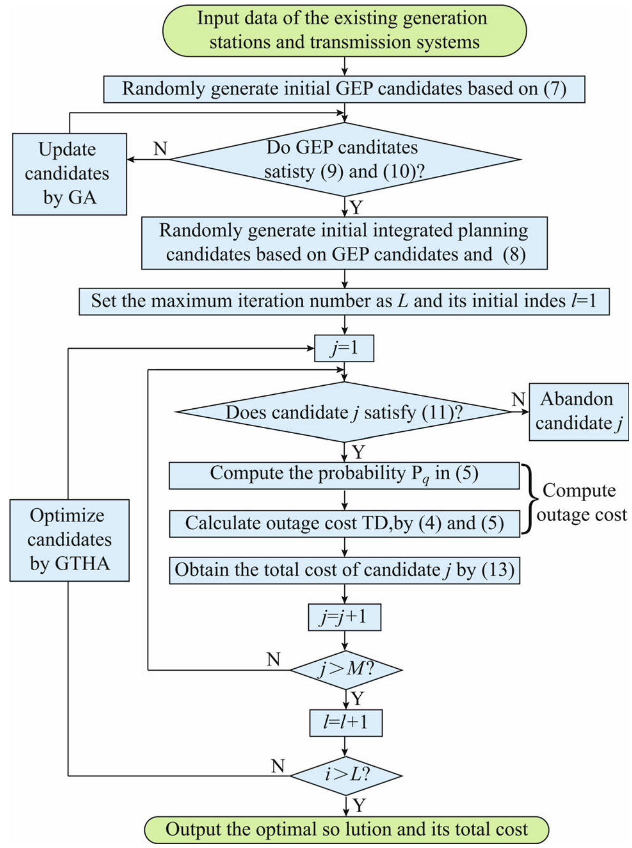

Fig. 1 Procedure of the proposed optimization method

Step 1: Input the initial data of the existing generator stations and transmission systems

Step 2: Randomly generate initial GEP candidates based on (8), which include only the decision variable X_{ti} in (2) but exclude n_{ti-j} in (3).

Step 3: Check if initial GEP candidates satisfy constraints (10) and (11). If so, go to Step 5; otherwise, proceed to Step 4.

Step 4: Execute the GA operation of crossover and mutation to update GEP candidates; and then return to the Step 3.

Step 5: Randomly generate initial integrated planning candidates, which include the decision variable X_{ti} and n_{ti-j}, based on the GEP candidates obtained through the above steps and (8).

Step 6: Set the maximum iteration number as L and its initial index $l = 1$.

Step 7: The integrated planning candidates, which are indexed by j, will be evaluated one by one. For the first one, let $j = 1$.

Step 8: Examine if the current candidate j satisfies constraint (12). If so, go to Step 9; otherwise, abandon this candidate.

Step 9: Compute the probability P_q in (5) by considering each possible fault state of candidate j.

Step 10: Calculate the outage cost TD_t of candidate j by (4) and (5).

Step 11: Obtain the total cost of candidate j by (14).

Step 12: Let $j = j + 1$; if $j > M$ (M is the total number of candidates), proceed to Step xiii); otherwise return to Step 8.

Step 13: Let $l = l + 1$; if $l > L$, the iteration is completed; go to Step xv); otherwise continue to Step 14.

Step 14: Optimize the integrated planning candidates by GTHA, of which the details will be elaborated later, and then go to Step 7.

Step 15: Output the optimized solution of the integrated planning problem and its total cost.

With Steps 2–4, the searching space can be considerably narrowed down. This could be explained as follows: If there are m platforms and n corridors need to be planned, the search space, denoted as 2^{m+n} [25], is too large to find the optimal solution. However, it is observed that most of planning candidates in the original searching space violate the constraints (10) and (11), due to insufficient generation. Those candidates remain infeasible regardless of how the transmission system is planned. Thus it is not necessary to conduct transmission planning for these candidates. In the proposed procedure, only the feasible GEP candidates are kept for the optimization to find the final optimal solution. As a result, the search space is greatly reduced to $2^m + 2^n$.

Noticeably, in Step 14 of the stated procedure, GTHA is applied to search the solution of the optimization problem (17) efficiently. Actually GTHA can be categorized as an improved GA with its mutation operation being replaced by Tabu algorithm. By this way, the implicit parallel property of GA is exploited to provide Tabu algorithm with initial candidates. Meanwhile the excellent local search ability of Tabu algorithm makes up the shortcoming of GA in local optimization. The detailed process of GTHA is illustrated in Fig. 2.

The parameters of GTHA should be carefully chosen in order to enhance its efficiency. It is discovered that its performance is especially sensitive to two parameters, i.e., the population size of GA and the maximum iteration number of Tabu algorithm. Larger GA population size could diversify the chromosomes but increase the computation time. A medium size of population, for instance, 90 in the problem, is found to be favorable. Similarly, when the maximum iteration number of Tabu algorithm is increased, the Tabu search process will be reinforced. However, the computation burden may be increased as well. After many experiments, the optimal maximum iteration number of Tabu algorithm is found to be 16 for the problem. By properly selecting these two parameters, the total computation time will be reduced by 80%. The other algorithm parameters can be easily optimized through trial and error. Their optimal values are listed in Table 1.

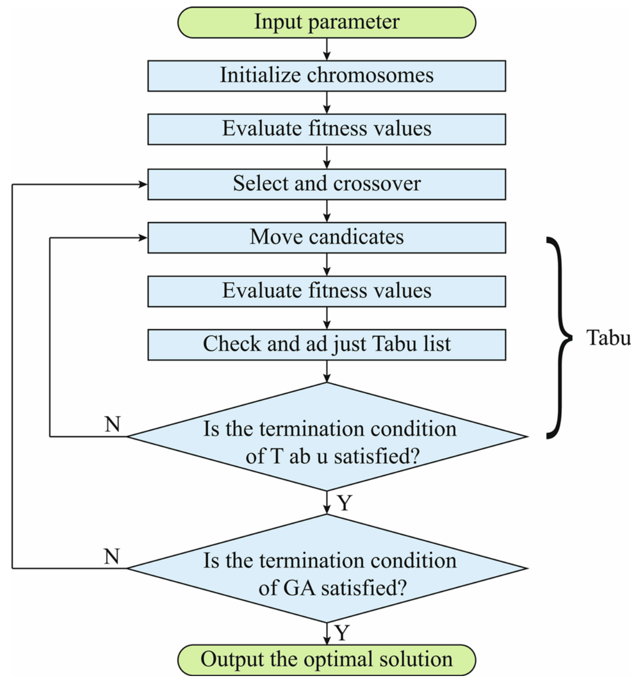

Fig. 2 Flow chart of GTHA

4 Case Study

An offshore power system test bed based on a practical oilfield group located on Bohai Sea is used for case study. Figure 3 shows the topology of this system. Currently, there are 25 gas-turbine generators with a capacity of 10.5 MW each and installed on 10 of the 47 existing platforms. Three new drilling platforms will be established in the next few years to exploit oil in the neighboring areas as indicated by A1, A2 and A3. To meet the steadily increasing load requirement, as shown in Table 2, as well as to improve the supply reliability, new generators and

Table 1 Optimized parameters of GTHA

Parameters	Value
Crossover probability	0.9
Maximum iteration number of GA	5
Population size of GA	90
Maximum iteration number of Tabu algorithm	16
Number of trial solutions in Tabu	24
Tabu length	2

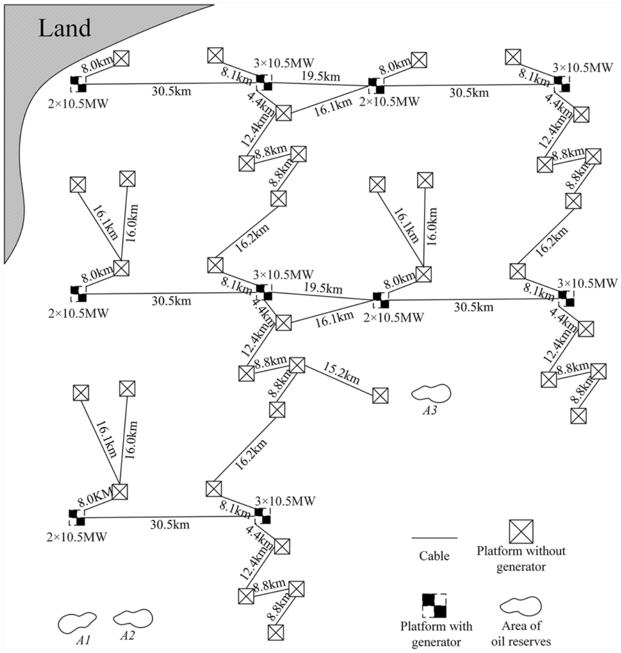

Fig. 3 Offshore oilfield power system before expansion planning

Table 2 Load demand of the system to be planned

	2015	2016	2017	2018
Capacity (MW)	229.700	316.700	422.800	462.400
Electricity (10^6 MWh)	1.286	1.773	2.368	2.590

cables should be planned for the offshore power system. Tables 3 and 4 provide the specifications of available generators and cables. The horizon is from 2015 to 2018. Two issues are of great concern for the case study, i.e., the efficiency of our proposed method and the impact of the outage cost on the result.

4.1 Efficiency of the proposed optimization method

The proposed planning procedure and GTHA, as well as a previously reported procedure [26] and the traditional GA [27], Tabu [25] and PSO [14] algorithms, are applied to the integrated planning problem (17) respectively to evaluate and compare their performances. The major difference between our proposed procedure and the one presented in [26] is that the latter does not use the three steps (i.e., Steps 2–4) to narrow the solution space by ruling out the planning candidates that

Table 3 Specifications of available generators [27]

Capacity (MW)	Investment cost (10^6 ¥/MW)	Operation cost (10^6 ¥/year)	FOR (%)
10.5	4.5	4.19	0.76

Table 4 Specifications of available cables [27]

Capacity (MW)	FOR (%)	R (Ω/km)	X (Ω/km)	Cost (10^6 ¥/km)
25	2.1	0.0778	0.121	1.70
35	2.1	0.0614	0.118	1.94

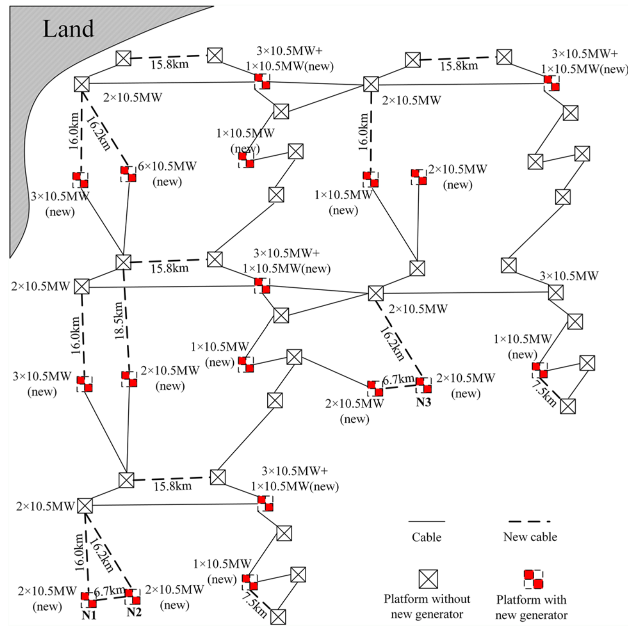

Fig. 4 Optimally planned offshore oilfield power system

violate the generation constraints (10) and (11). All procedures and algorithms are implemented in MATLAB and executed on an Intel Xeon E5-2650, 2 GHz, 4 GB RAM computer. The optimal plan obtained by our proposed method is illustrated in Fig. 4. The total cost of the solution and the computation time consumed are listed in Table 5.

Table 5 shows that the total costs of the solutions obtained by the two procedures are similar. However, the computation time of our proposed procedure is about one third of that of the procedure reported in [23], which fully demonstrates the effectiveness of the steps proposed for narrowing the solution space of the problem.

It can be seen from Table 5 that GTHA provides the most cost-effective solution with the least computation time. The computation time of GTHA is only about one-tenth of the Tabu algorithm. On one hand, by inheriting the excellent local search ability from Tabu, GTHA resolves the premature convergence problem of GA and PSO. One the other hand, GTHA utilizes the implicit parallel property of GA to make up the shortcoming of Tabu in problem-solving speed. These results validate the effectiveness of our proposed procedure and algorithm in solving the expansion planning problem.

Table 5 Total cost and computation time

	Our proposed procedure		Procedure in [26]	
	Total cost (billion/¥)	Computation time (min)	Total cost (billion/¥)	Computation time (min)
GA	2.79	4320	2.79	13824
Tabu	2.24	4528	2.24	14324
PSO	6.11	1962	6.11	5755
GTHA	2.24	494	2.24	1581

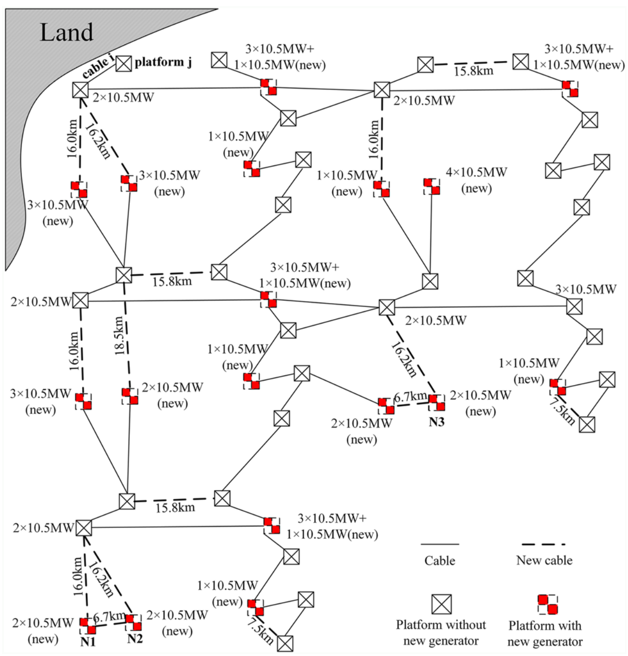

Fig. 5 Optimally planned offshore oilfield without the consideration of outage cost

4.2 Impact of outage cost on expansion planning

In the proposed planning model (17), the outage cost is taken into account. To further investigate how the cost affects the planning of the offshore oilfield power system, we intentionally ignore the cost and solve the optimization problem again. The newly obtained result is shown in Fig. 5. The corresponding total and outage costs with and without outage cost considered are listed in Table 6. It is clear that the outage cost of the plan obtained by the proposed model (i.e., 0.13 billion/¥) is only 5% of that of the model without considering the outage cost (i.e., 2.38 billion/¥). Consequently, the total cost of the former is much smaller than the latter, indicating that if outage cost is explicitly taken into account, a much more cost-effective expansion plan could be obtained. By comparing Fig. 4 with Fig. 5, we can see that with the consideration of outage cost, there will be more new generators and cables to be constructed in order to satisfy the "$N-1$" security criterion or reduce loss caused by power outage. In contrast, if outage cost is ignored during the planning stage, the resulted system is much more vulnerable to power blackout. For instance, if the cable i at the upper-left corner in Fig. 5 is out of service (a typical "$N-1$" event), platform j at the top left corner will become an isolated subsystem. However, without any generators in it, it would suffer serious power blackout. Therefore, outage cost should be taken into account to plan a more reliable offshore oilfield power system.

5 Conclusion

In this paper, we propose an integrated generation-transmission expansion planning model to address the issue of updating offshore oilfield power systems for providing efficient and reliable electricity to offshore drilling platforms. The integrated model inherently overcomes the disadvantages of planning generation and transmission separately. The simultaneous and optimal expansion planning is formulated into a mixed integer programming

Table 6 Costs of the planned system with/without the consideration of outage cost

Model	Model with outage cost	Model without outage cost
Number of new generators	33	32
Number of new cables	16	15
Investment cost of generators (billion/¥)	1.56	1.51
Investment cost of cables (billion/¥)	0.38	0.35
Operation cost of generation system (billion/¥)	0.02	0.02
Operation cost of transmission system (billion/¥)	0.15	0.15
Outage cost of plan (billion/¥)	0.13	2.38
Total cost of plan (billion/¥)	2.24	4.41

problem, which is difficult to solve due to its multiple variables and nonlinearity. Therefore we present an efficient solution based on GTHA, which combines the implicit parallel properties of GA and the powerful local searching ability of Tabu algorithm. The proposed model and optimization method are applied to an offshore power system based on the Bohai sea oilfield. The results of this case study show that the computation time of the proposed method is about one third of the previously reported method and GTHA converges much faster than GA and Tabu algorithm. By incorporating the outage cost explicitly in the proposed model, the reliability of the obtained system can be enhanced considerably and the total investment cost is reduced by about 40%.

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